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The climate change impact on air conditioner system and reliability in Malaysia—A review

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ABSTRACT

This paper presents the studies conducted on the effect of climate change on the air conditioner in terms of performance and reliability in the tropics. Basically, three aspects of impact were focused, which were cooling and heating load, electricity consumption and outdoor design conditions for the air conditioning system. The related papers were categorized into three groups and analysis of theoretical and experimental studies was made. A lot of researches had been carried out on the climate change impacts towards the air conditioner in the tropics since last few decades, but most of the researches were focused on existing cooling or heating demands, region overall electricity consumption and existing outdoor design conditions for the air conditioning system instead of the possible impacts on the heating, ventilation and air conditioning system in the future. Based on literature review, further substantial researches are needed in order to have a clearer picture on the climate variation effect towards the air conditioning system so that a complete guideline can be prepared for the future air conditioning system design in the tropics by taking consideration of possible climate change.

Contents

1. Introduction

Air conditioner is no longer luxury product due to the improvement in technology that lowers down the air conditioner cost. Instead, it has become a need due to the critical climate change nowadays. Many Southeast Asian countries like Malaysia experience hot and humid climates, which result in the air conditioning system in the residential sector within Malaysia has increased sharply from thirteen thousand to seven hundred seventy five thousand in 2000 [1,2] with the increment more than 5000% and this increment will be more unimaginable with critical climate change. On the other hand, other researches have stated that roughly 30% ready use energy throughout the world is applied in the residential sector and about 50% end use energy in household area is consumed in warming application [3]. Most of the households are using the wall-mounted air conditioner due to the easy installation and low cost. Thus, the future performance and development of the just mentioned air conditioner will certainly affect the energy demand worldwide greatly.

Commercial wall mounted air conditioner is classified as the direct expansion air conditioner system that utilized evaporation and condensation of refrigerant only in the system for cooling or heating purpose. Refrigerant is a highly evaporative substance that can easily absorb heat, expand and evaporate or condensate by releasing heat. The most common refrigerants used in the wall-mounted air conditioner are R410A, R407C and R22.

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Nomenclature

ADAM	Adaptation and Mitigation Strategic project
ANETZ	Swiss Automatic Measurement Network
AO-GCM	Atmosphere–Ocean General Circulation Models
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineer
ASHRAE_ MAX_1	the highest ambient data provided by ASHRAE
ASHRAE_MAX_2	the highest ambient data provided by ASHRAE
ASHRAE_MAX_04	the highest ambient data provided by ASHRAE
ASHRAE_04	design condition recommended by ASHRAE
ASHRAE_1	design condition recommended by ASHRAE
ASHRAE_2	design condition recommended by ASHRAE
ASHRAE_EVAP_04	design condition recommended by ASHRAE
ASHRAE_EVAP_1	design condition recommended by ASHRAE
ASHRAE_EVAP_2	design condition recommended by ASHRAE
BLAST	Building Loads Analysis and System Thermodynamics software
Bldg-1	first case building
Bldg-2	second case building
CDD	cooling degree day
CURRENT	existing ambient design data used for application in Turkey
DOM	Day time Operation Mode
DAILY MAX	the highest ambient data daily of July 21st in Turkey
DATA (61-90)	weather data file that was generated using the MeteoNorm software based on measured weather data in Bahrain from 1961 to 1990
DATA (61-05)	weather data file that was generated using the MeteoNorm software based on measured weather data in Bahrain from 1961 to 2005
EC	total monthly electricity consumption in Bangkok Metropolis
ESCAPE	evaluation of strategies to address climate change by adapting to and preventing emissions model
EMPA	Swiss Federal Laboratories for Materials Testing and Research
GP	grid point
GCM	global climate model
HDD	Heating Degree Day
HVAC	heating, ventilation and air conditioning
IEA	International Energy Agency
IMAGE	integrated model to assess the global environment climate model
IPCC	Intergovernmental Panel on Climate Change
M&E	mechanical & electrical
NOM	Night time Operation Mode
PC	personal computer
PRECIS	providing regional climates for impacts studies climate model
RAC	room air conditioner
REC	residential electricity consumption
RECB	residential electricity consumption of Bangkok metropolis
TIMER	Targets Image Energy Regional simulation model
TRY	test reference year
TRNSYS	transient system simulation program
US	United States
θ_{th}	threshold temperature for heating
$\theta_{e,k}$	daily mean external temperature
θ_i	internal temperature
Q_h	yearly warming energy that is needed for a space
K_{tot}	heat losses by convection and leak through building
Q_s	heat gains inside the building and radiation energy from sun
n	a ratio in terms of heat gains inside the building and radiation energy from sun which reduce warming needs
T_a	monthly mean ambient temperature in Bangkok
ΔEC	changes in total monthly electricity consumption in Bangkok metropolis
ΔEC (T_a+1)	difference in consumption due to 1 °C rise in temperature
Δh	design enthalpy difference
k	quantity of days within a year

In general, the wall mounted air conditioner can be divided into two units, which are the indoor unit installed in indoor to absorb heat (for cooling) or release heat (for heating) and the outdoor unit fixed in outdoor to function in the reverse order with the indoor unit. There are two types of wall-mounted air conditioner, namely the air cooled type using air as the medium to absorb or release heat from the refrigerant in the outdoor unit and the water cooled type using water as the medium.

For the wall-mounted air conditioner with cooling function only, the indoor unit consists of an indoor heat exchanger only while the outdoor unit is equipped with an outdoor heat exchanger, compressor and expansion device. In a country with seasonal climates, most of the households are using the heat pump type wall-mounted air conditioner to perform cooling or heating. The difference between the heat pump and cooling only air conditioner is the outdoor unit of the heat pump has one more component known as the four-ways valve. The main function of the four-ways valve is to change the flow of the refrigerant system from cooling mode into heating mode or in reverse order according to the user. Fig. 1 shows how the refrigerant flows inside cooling only air conditioner. Figs. 2 and 3 show the refrigerant flows during cooling and heating mode heat pump type air conditioner.

In the recent years, numerous researches had been done regarding the impact of climate change on the air conditioner system from different aspects throughout the world [4–6]. However, only the literature related to the effect of weather change on air conditioner performance and reliability is reviewed in this paper. This literature summary consists of three parts, which are the climate change impacts towards cooling and heating loads, the effect of weather change on the air conditioner power consumption and impacts on outdoor design conditions due to climate variation.

2. Climate change impacts towards cooling and heating loads

Climate change impacts towards worldwide is unavoidable. As what has forecasted by Intergovernmental Panel on Climate Change (IPCC) [7], the ground temperature will raise roughly 1–6 °C from 1990 to 2100 due to the critical weather variability and extreme event. However, in Europe, most of the countries import oil for boilers or furnaces to provide space heating, and it consumes around 50% of the primary energy used in the Europe [8]. The exploitation of this natural resource tends to release greenhouse gases and further increases global climate change rate. As a result, rise of sea level, rapid heat waves and others disasters happen more frequently.

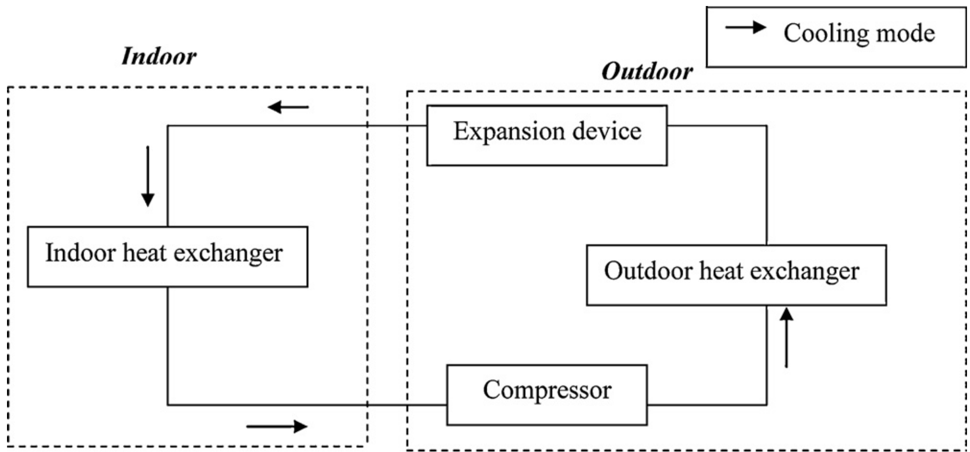

Fig. 1. Refrigerant flows inside cooling only air conditioner.

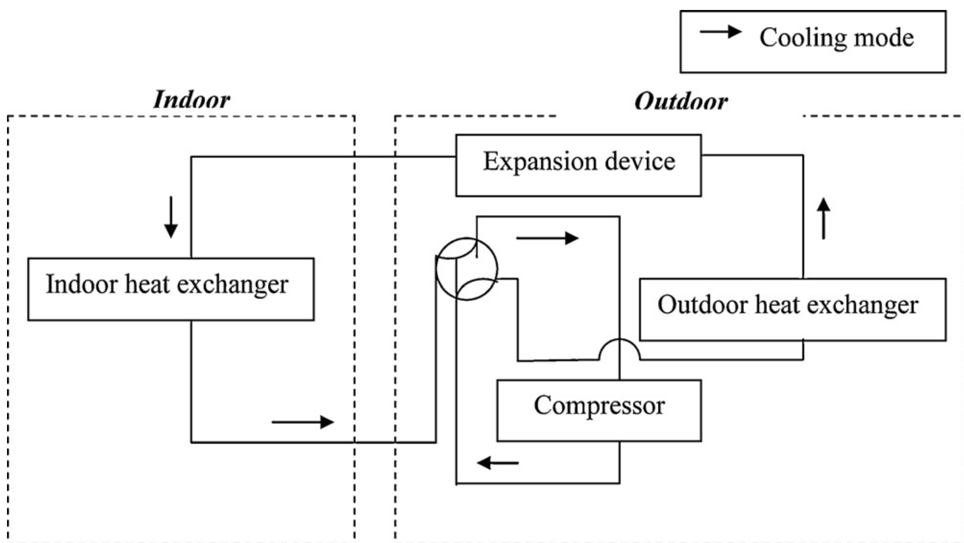

Fig. 2. Refrigerant flows during cooling mode heat pump type air conditioner.

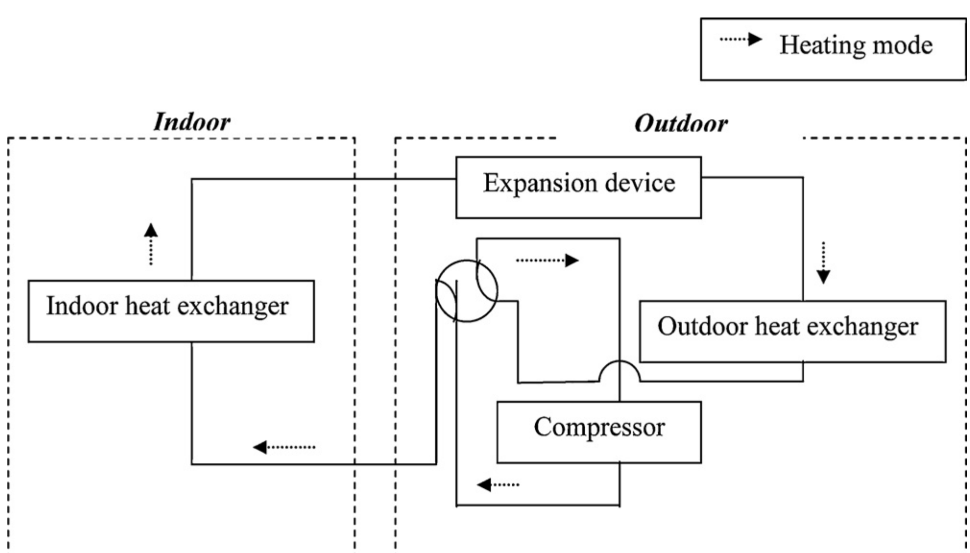

Fig. 3. Refrigerant flows during heating mode heat pump type air conditioner.

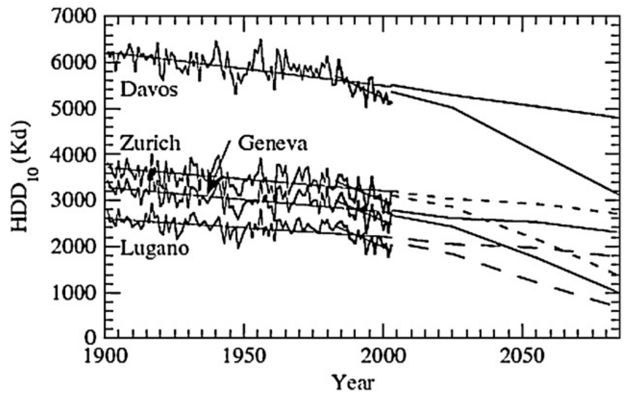

Fig. 4. Heating Degree Day (with threshold temperature = 10 °C) for four places was calculated using data every month [11], the correction function and GP temperature estimation are taken from Ref. [13].

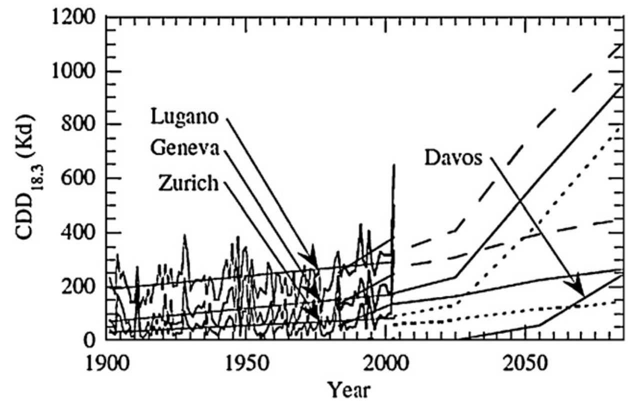

Fig. 5. Previous cooling degree day (with threshold temperature = 18.3 °C) from 1901 to 2003 and estimation future cooling degree day from 2004 to 2085 using the GP temperature estimation obtained from Ref. [13].

Due to the great impacts of weather change to the world, researchers had carried out plenty of studies with different methods focused on few aspects such as agricultural sector, economic sector and others. Generally, most of the researchers have applied the degree days approach, the detailed numerical building simulation or the experimental studies to investigate the weather variation impact towards cooling and heating loads of the air conditioner.

The degree-day methods are the popular, relatively easy and fairly reliable tool to assess heating and cooling loads. However, this method only accurate if the heat transfer through a building is in the steady state. The degree-day methods are widely used and defined in the different form mainly depending on the applications. An example of the degree-day methods for heating is from a Swiss standard [9]:

$$\mathrm{HDD}(\theta_i, \theta_{th}) = m_k \sum_{k=1}^{n} (\theta_i - \theta_{e,k}); \quad m_k = 1 \quad day \quad if \quad \theta_{e,k} \leq \theta_{th},$$
$$m_k = 0 \quad day \quad if \quad \theta_{e,k} \geq \theta_{th} \tag{1}$$

In Eq. (1), θ_{th} is the threshold temperature for heating, $\theta_{e,k}$ is the daily mean external temperature, k is the quantity of days within a year, $k \in \{1, \ldots, 366\}$, and θ_i indicates the internal temperature. θ_{th} value is determined based on the regional standard and influenced by the level of building insulation and the higher level of insulation results lower θ_{th}. From Eq. (1), the yearly warming energy needed for a space, Q_h, is represented by:

$$Q_h = K_{tot}\mathrm{HDD} - nQ_s \tag{2}$$

K_{tot} represents the heat losses by convection and leak through building, Q_s represents the heat gains inside the building and radiation energy from the sun, while n denotes a ratio in terms of Q_s, which reduces warming needs.

Christenson et al. [10] applied the degree-days method to study the weather variation effect to four Swiss-located building power consumption in the past from 1901 to 2003 and in the future from 1975 to 2085. Begert et al. [11] published information about the four main places, namely Geneva, Zurich, Lugano and Davos. The measured climate database from 1901 to 2003 was applied, which was obtained through an automatic measurement network (ANETZ). Subsequently, the ambient data for every month throughout the period was formed and tested using previous data to investigate the impacts. On the other hand, the trend from 2000 to 2100 was predicted applying the simulation data through the coupled Atmosphere–Ocean General Circulation Models (AO-GCM) [12].

Figs. 4 and 5 illustrate the trends of the HDD and CDD from the past to the future. The result showed that the Heating Degree Days reduced around 11–18%, and it was affected by places as well as the threshold temperature during 1901–2003. Besides, it also predicted that there could be an additional reduction from 13% to 87% in the future (1975–2085). The trend indicated that the cooling degree days increasing significantly, especially from 1901 to 2003 with more than 2100% increment in the future. From the study, the existing climate result applied in Switzerland building design tends to overestimate the warming and underestimate the cooling needs resulted in the overheating problem occurs in the future.

The detailed numerical building simulation modeling is another popular method used among researchers to access climate change impacts to the warming and cooling demand. The degree-days is a simpler method, but it is limited to the steady state condition, and it is not practical since the different buildings employ different thermal insulation levels, heat gains and losses throughout the seasons and day night time. Thus, the building simulation is used to solve this problem, and the high-ended powerful software has been designed for this purpose such as HELIOS [14], DOE-2 [15], BLAST (built in the University of Illinois) [16], TRNSYS (built in the University of Wisconsin) [17], TIMER energy model [18], and EnergyPlus [19]. Although these powerful software can predict the cooling and heating load variations due to the climate change effect accurately, they need two major inputs in order to perform the simulation. The first data is the detailed building model description such as the orientation, dimension, internal temperature parameters, air ventilation rate and solar heat gains coefficient. The second data is the complete climate database like the wind orientation, wind speed and wet bulb temperature. The main climatic components include the air velocity, air temperature in a long term and standard timescale data are needed in order to generate a good weather data collection. There are two general ways to form a weather database, namely the simulation approach and the statistical approach. The first method is using the simulation software to generate the climatic data while the second way is using the statistical method to record down weather elements in a fix time frame. Some of the statistical approaches utilize the existing climatic model like ESCAPE [20], PRECIS [21], survey method and measured climatic data from a weather station such as ANETZ [22]. Among these, the surveyed and measured climate data are the popular tools in Hong Kong [23–27]. In addition, a numerous amount of popular weather data generators are available to form a detailed weather database such as RUNEOLE [28], TRY software [29], MeteoNorm [30] and TRNSYS [31] software. However, the combination of two methods to use the statistical data for compiling a detailed climate database based on actual measured data is widely used now among researchers.

In Frank's study [22], the potential weather variation effect on the cooling and warming needs in Zurich-Kloten region, which

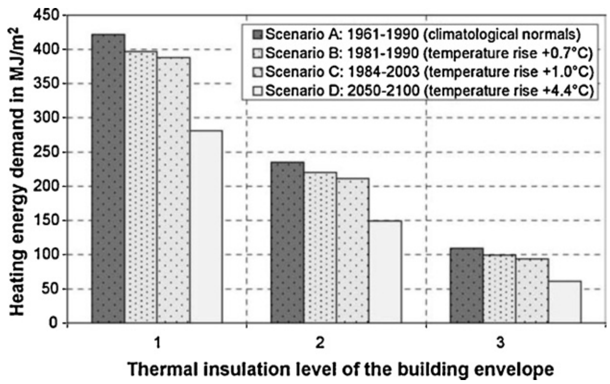

Fig. 6. Warming needs in a household building yearly with different thermal properties.

represented the weather in Swiss Central Plateau was investigated by using the transient building energy simulation software, HELIOS [14]. HELIOS is a simulation software works on the steady state heat transfer throughout a defined space. For weather data input, the hourly climate data during period 1981–2003 for Zurich-Kloten (47.29N/8.32E/436 m) was accessed in the database of ANETZ by using a software tool developed by EMPA [32] and the four different climatic scenarios from different sources [33–38] were used to investigate the weather variation effect. In addition, a building with predefined, detailed thermal properties and other details were used in HELIOS in combination with the weather data above to simulate the cooling and heating load trend. The result in Fig. 6 shows warming needs in the household buildings yearly with different thermal properties. Figs. 7 and 8 present the cooling and warming cooling needs yearly for commercial buildings 1 and 2 with different thermal properties.

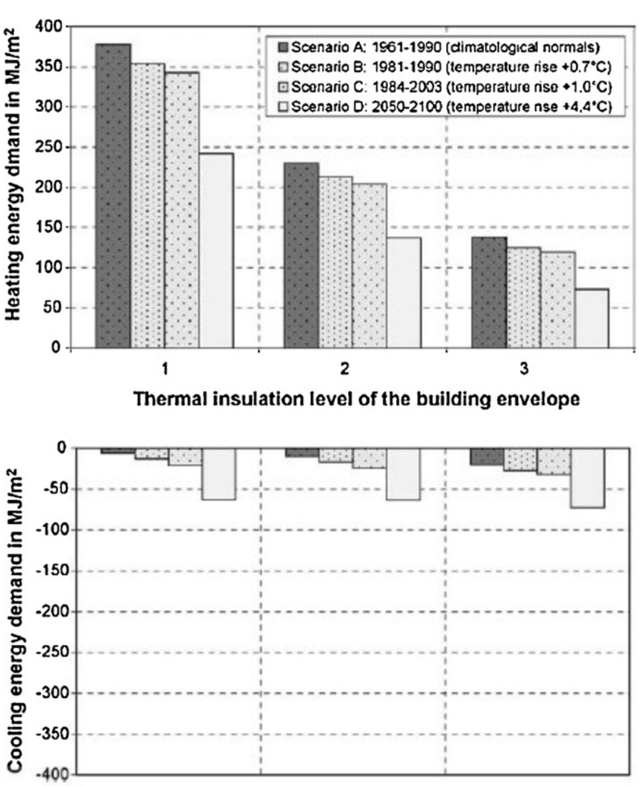

Fig. 7. Cooling and warming cooling needs yearly for commercial building 1 with different thermal properties.

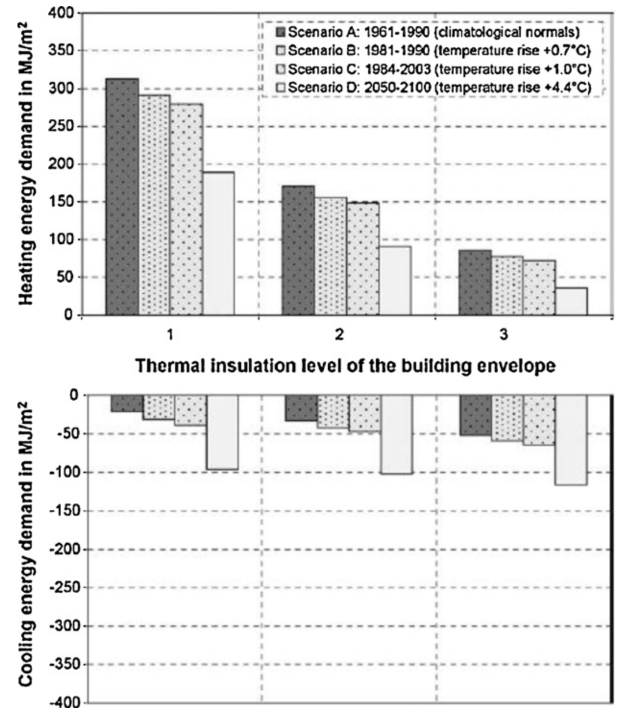

Fig. 8. Cooling and warming cooling needs yearly for commercial building 1 with different thermal properties.

The result shows that there will be a rise in the mean annual air temperature from 2050 to 2100 in comparison to the previous time and thereby similar to the weather variation estimated by the Intergovernmental Panel on Climate Change (IPCC), which leads to the higher overheating risk. The calculation result also predicts that the household in Swiss will experience around 30–40% reduction in the warming needs yearly from 2050 to 2100. On the other hand, the warming needs yearly will decrease roughly 36–58%, and the cooling needs yearly for commercial buildings will rise up sharply from 223 to 1050%. The result also predicts that the warming period will be shortened around 50 days and suggests a good solar energy prevention such as the tinted technique shall be focused in the future in order to maintain a good indoor thermal comfort.

Lam from Hong Kong [26] uses DOE-2.1E software to investigate the weather variation effect to the power consumption and heat load for commercial buildings from 1979 to 1995. Three aspects are focused in the studies, which are the annual power usage, annual cooling load and maximum cooling load. The maximum cooling load will affect air-conditioning plant designs and sizing while the cooling load yearly will influence cooling demand in cooling period. Note that the annual electricity consumption is emphasized in this study because 40–60% of the power consumption in commercial buildings in the subtropical Hong Kong uses in the air conditioner for the cooling purpose [39]. In order to develop a realistic building model for simulation, a study about office buildings in Hong Kong was carried out to look for the general design to represent the office buildings in Hong Kong [39]. Based on the survey, a forty-level commercial building model, which is air conditioned and equipped with the curtain wall was developed for this simulation in the investigation. For the climate data input, the annual climate data from 1979 to 1995 of Hong Kong were successfully compiled [40].

In order to study the different climatic data effects to the three parameters, the test reference year (TRY) represented by the year 1989 for Hong Kong and seventeen years average monthly cooling needs were used as a reference in the study [43–45].

Fig. 9 shows the estimations using the average monthly cooling needs and TRY indicated that the biggest difference within the

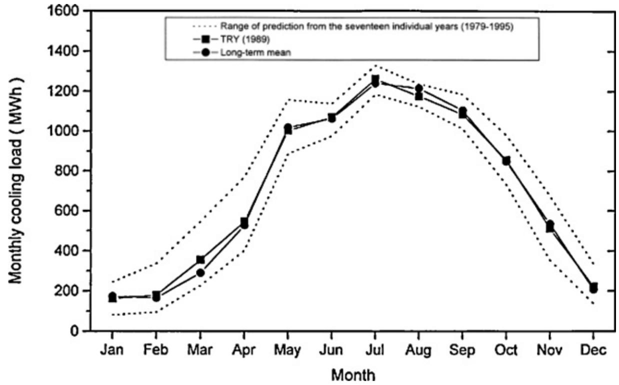

Fig. 9. Difference of the cooling need estimation with the test reference year and average monthly value.

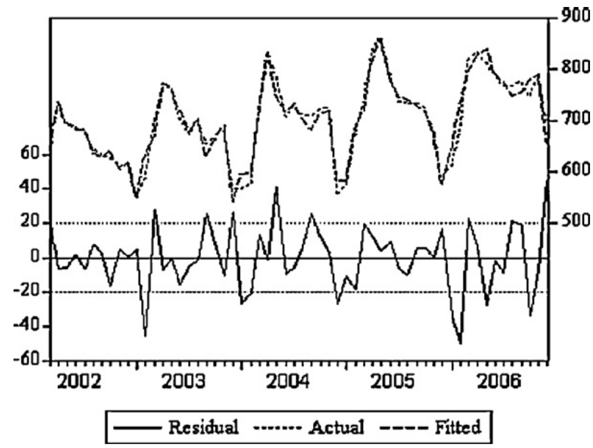

Fig. 10. Comparison of actual and predicted data from RECB.

17 years is 8.2% of the average cooling needs yearly. On the other hand, the maximum cooling demand also changes regularly with roughly 14% of the 17-year average value. In the study, the estimations using the test reference year quite similar to the seventeen years average value shown that the TRY can be used as a good design criterion in the building energy design.

For the room air conditioner (RAC) design, the current practices are always focusing on the daytime and neglecting the nighttime bedroom air conditioning. As a result, the oversized problem happens to result in the great fluctuation of room temperature and causes thermal discomfort to the user. Thus, Lin and Deng [27] reported on a simulation study using EnergyPlus [19] on the nighttime bedroom cooling demand in the tropics and subtropics. A thirty-level household building represented a common building in Hong Kong was modeled in the software. Each floor of the residential block consists of eight units with the share elevator lobby/staircase. For the climate data input, the room temperature set point with 23 °C was input into Energy Plus. The highest ambient temperature, the average wet-bulb temperature and temperature variation for the summer design day for Hong Kong in 24 h were chosen at 33.2 °C, 26.1 °C and 4.5 °C, respectively [44] with the 4.5 °C fluctuation value scattered over 1 day sinusoidally. In addition, a weather database for 1989 has been compiled as the input and simulation were carried out in the summer period. The output showed that the cooling demands in sleeping rooms at the Night time Operation Mode (NOM) were significantly different from those at the Day time Operation Mode (DOM). At the NOM, the earlier part of cooling process was mainly caused by the thermal energy absorbed by the building envelope. Besides, the yearly total cooling demand was found greatly affected by the indoor design air temperature. In addition, the result also showed that the orientation affected the cooling demand in the DOM greatly, but not in the NOM. This result suggests that the use of a smaller size of the room air conditioner in sleeping room is recommended instead of using the maximum cooling demand in order to reduce the minimum number of off-cycles.

3. Effect of weather change on HVAC system energy usage

Worldwide HVAC system energy usage is increasing dramatically due to economic, climate and other factors. The air conditioning has consumed more than 60% of electricity in a hot climate city like Jeddah, Saudi Arabia [45]. Some research work on residential energy consumption in several Asian cities [46–51] showed that the less income group is also willing to spend for electricity as a result of rapid economic growth for thermal comfort. In addition, climate change has increased the ambient temperature. Consequently, the increased ambient temperature demands the growing need of electricity for the air conditioning and consumes a significant amount of electricity for Jeddah in the summer implied that the effect of climate change to the air conditioner power consumption is a reality [52].

The researches above showed that the climate change and energy sector are strongly related to each other. Weather variability will greatly affect the heating and cooling demand and the combustion of fossil fuels in the energy sector produces greenhouse gases due to the cooling or heating demand result in serious climate change [53]. The Intergovernmental Panel on Climate Change (IPCC) has published a report recently to warn people about the impacts of energy exploitation on environment [54]. Hence, researches were carried out to study the weather change impacts on renewable energy sources, especially on the hydropower generation [55,56] and wind energy availability [57,58]. In energy demand view, the weather variation impact on electricity demand has been studied recently [59–61] and used to predict electricity in short and mid term period [62–64]. Some of the researches investigated weather change impact on electricity consumption at the level of the individual building such as commercial building as mentioned in Scott et al. [65].

Many studies have been carried out to investigate the weather change impact on air conditioner power consumption, but the approaches used are similar to the cooling and heating load related researches. The general methods widely used are the degree days approach, detail numerical building simulation and experimental studies. Besides, there are some studies use the mean outdoor temperature and/or degree-days data in investigating the energy consumption at regional scales such as the gas and electricity consumption in the US [66–68].

For degree days approach, Kiattiporn et al. [69] studied and claimed that the residential electricity consumption (REC) within Bangkok Metropolis rose over 200% since 1980. In this study, the residential electricity consumption of Bangkok Metropolis (RECB) model was developed to investigate the climatic and economic factors affecting the REC in Bangkok Metropolis from 2002 to 2006 using the stepwise multiple regression technique. The time-series data of monthly electricity consumption from 2002 to 2006 have been used and the data showed that the trends of the climatic and economic factors can be utilized to predict the REC in terms of trend, seasonal variation, business cycle and irregular variation. Table 1 indicates the result of the direct climate effects on the electric power usage. Fig. 10 shows that the RECB model has more than 95% accuracy.

In another study, Lam et al. [24] studied the climate change impact towards the electric power usage in Hong Kong. Forty-years (1961–2000) ambient data were collected and analyzed in

Table 1
Impacts of 1, 2, and 3 °C increment to ΔEC in household power consumption monthly in year 2006.

Calculating of monthly ΔEC in REC due to 1, 2, and 3 °C that rose in the year 2006					
Month	T_a (°C)	EC (actual)	ΔEC (T_a + 1) (GWh)	ΔEC (T_a + 2) (GWh)	ΔEC (T_a + 3) (GWh)
January	27.9	611.73	87.26	140.05	192.84
February	29.4	684.67	102.5	155.29	208.08
March	30.2	818.88	30.71	83.5	136.29
April	30.8	834.28	45.32	98.11	150.9
May	30.1	811.53	80.06	132.85	185.64
June	29.4	788.96	55.03	107.82	160.61
July	29.5	766.34	61.06	113.85	166.63
August	29.2	766.85	31.36	84.15	136.94
September	28.8	772.81	34.34	87.13	139.92
October	29.2	745.37	85.92	138.71	191.5
November	29.9	781.77	59.95	112.74	165.52
December	27.5	695.97	7.18	59.96	112.75
Average		756.6	56.72	109.51	162.3
%Change			7.49	14.47	21.45

T_a is the monthly mean ambient temperature in Bangkok. ΔEC (T_a + 1), ΔEC (T_a + 2), and ΔEC (T_a + 3) stand for the difference in consumption due to 1, 2, and 3 °C rise, respectively.

terms of the cooling degree days (CDD), average temperature and cumulative frequency of happening. The mean temperature result showed that the temperature rises in recent years and happens more rapidly in the mid-season and winter. On the other hand, the frequency of happening result indicated that the variation in the maximum cooling demand and outdoor design conditions was negligible. Moreover, the cooling degree days with four threshold temperatures from 17 to 20 °C were determined and are presented in Fig. 11. Based on the result, the CDD fluctuated around 5% of the average value of the period and the power usage could be used to predict the models using the regression method. Note that the CDD should include a minimum 5% tolerance in the electricity consumption estimation due to the CDD variations.

In another investigation, Isaac and Van Vuuren [70] examined the weather variation impacts globally to the household electric power needs for the cooling and warming purposes. In this research, the energy required was determined using the equation from Schipper and Meyers study [71]. The result was then divided using the small-part approach used by IEA in the Energy Indicator Project [3] with the baseline temperature at 18 °C worldwide. Besides, models from the TIMER/IMAGE reference model in the ADAM project were used in the research [72]. The projected future trend of worldwide energy needs by the cooling and warming purposes is shown in Fig. 12. The result indicates that the weather variation increases the cooling needs around 70% and reduces the global warming needs by over 30%. In addition, the great effects are found in the South Asia with the increased household cooling energy usage maybe increase by 50% caused by the weather variation compared with the condition without weather variation.

Air conditioning power consumption is critical, especially in the high ambient places like Jeddah, Saudi Arabia where the annual increment of electricity needs is one of the biggest globally [52]. Thus, Al-Rabghi et al. [45] compared the measurement and simulation results about the changes of electricity usage caused by an HVAC system. In the measurement section, the Solar Energy Building owned by the Thermal Engineering Department, King Abdulaziz University was used to carry out the experiment. In the study, measurement devices were commissioned to take electricity usage data in different conditions. A datalogger was installed to record air conditioner electricity. Also, a separate datalogger was fixed in the solar energy laboratory to collect data for the indoor and outdoor air conditions as well as the solar intensities. Fig. 13 shows the experimental result for the air conditioner electric power consumption from 22 to 25 in October 1997. Note that the AC power consumption was roughly 65 kW, and the ambient variation contributed 5 kW or around 7% variation to the power consumption. The 12 kW power consumption represented total electricity usage except chillers indicated that compressor consumed roughly 38 kW. As a summary, the total power usage of every big compressor is 26 kW. The result showed that the system experienced regular thermal on-off cycle due to the oversized air conditioner and poor control strategy.

For simulation work, Visual DOE-2.5 [73] was used to simulate the actual building data on an hourly basis based on information from the final technical report [74]. The result in Fig. 14 indicates that the measured and predicted electric usages are similar. In addition, the highest value of 27 kW is needed to operate the air

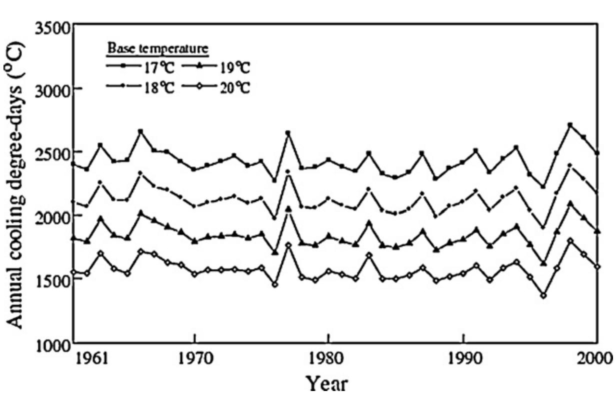

Fig. 11. Cooling degree days yearly based on the four threshold temperatures from 1961 to 2000.

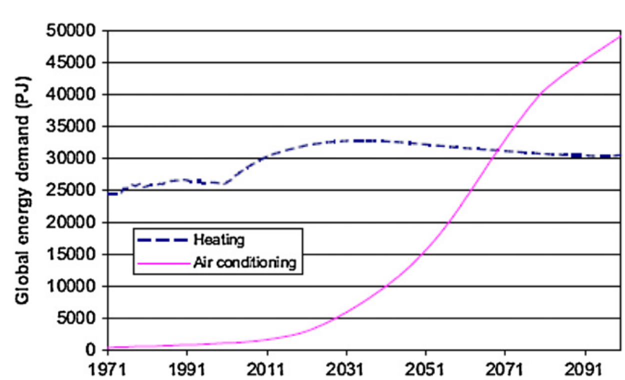

Fig. 12. Worldwide household energy needs for cooling and warming in a reference scenario.

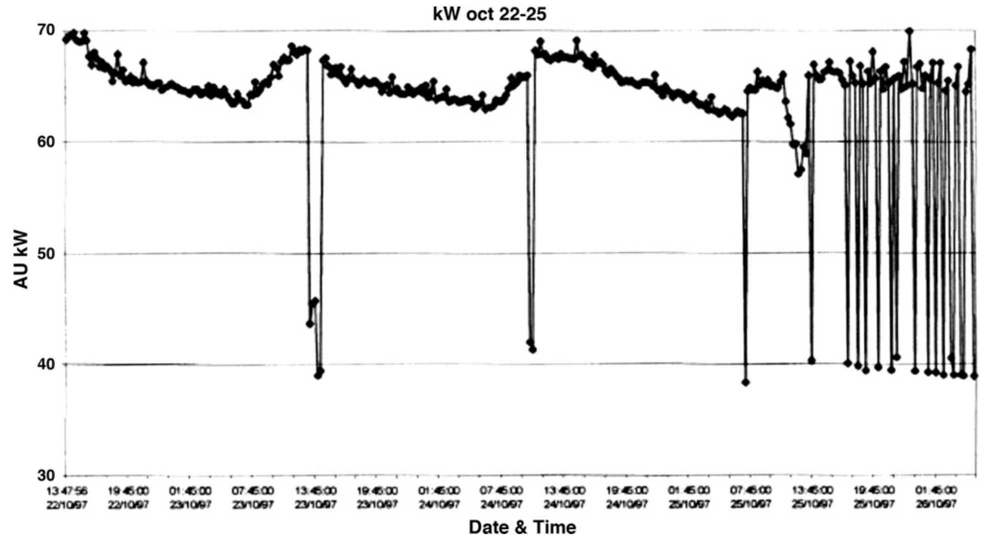

Fig. 13. HVAC system electricity usage during October 22–25, 1997.

conditioning system from Monday to Wednesday. However, only 22 kW and 21 kW are required for Thursday and Friday respectively due to the different building occupancy.

The multiple regression method is a popular method widely used to investigate power consumption due to the weather variability. In Hong Kong, the simple regression analysis techniques using the degree-days and mean monthly outdoor dry bulb temperature were applied in the earlier research on residential sector electricity [75]. Sailor [6] created a multiple regression model to investigate the power consumption due to the weather variables for eight states in the US using specific temperature change scenarios resulting from three different global climate model (GCM) simulation. The results showed that most of the states facing great increases with the exception of only one state experiencing the decreased electricity demand. In another study, Parkpoom et al. [76] applied the same method to predict the impact on electricity usages due to climate change in Thailand. He assumed that the uniform temperature increase of up to 4 °C in the steps of 1 °C. However, both studies are lack of non-climatic factors resulting in the weather variability impact on electricity demand is greatly affected.

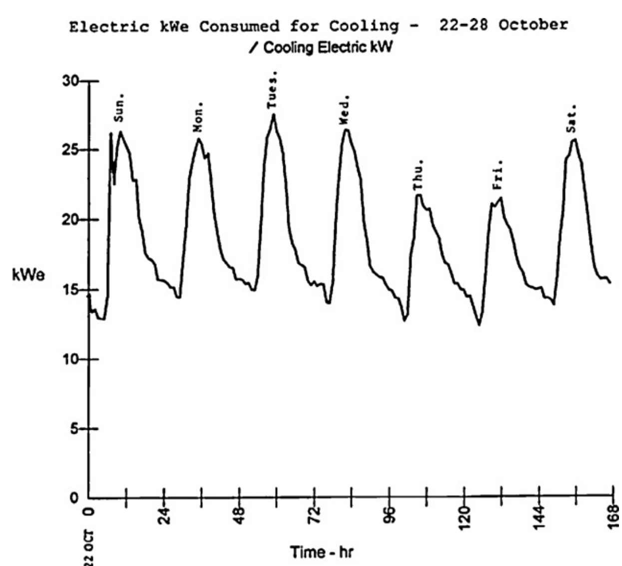

Fig. 14. Cooling electric kW required to overcome cooling load (October 22–28, 1997) [47].

On the other hand, Ruth and Lin [77] studied the weather variability impact on electricity consumption in Maryland with the multiple regression model method taken into account of non-climatic as well as weather factors. The study claimed that social-economic factor such as the regional population has greater impacts on the future power consumption in Maryland compared with the climate change. In addition, the similar method was used by Amato et al. [78] in a separate research on Commonwealth of Massachusetts, and the result again showed that there was a remarkable change in the overall power consumption in residential and commercial sectors due to the weather variation.

In a similar research, Mansur et al. [79] developed a multinomial discrete–continuous fuel choice model for residential and commercial sectors in the US to study the impact on energy demand due to possible future weather variability. The study generally suggests the same outcome as others, whereby the energy demand will increase due to the increase of temperature up to 2100. However, the most important discovery in this study is the high tendency to change fossil fuels to electricity due to global warming resulting in the electricity demand increases greatly in the future.

4. Impacts on outdoor design conditions due to climate variation

The outdoor design condition is a collection of climatic data at a particular location for certain period and usually used widely by the air conditioner system designers at that area. Indoor and outdoor design conditions are widely used in HVAC system design to estimate the peak design load [80]. It is a crucial factor in the HVAC system design because it determines the size and efficiency of an AC plant and varies depending on locations and applications. If the very extreme and conservative conditions are taken, the system causes thermal discomfort due to the rapid thermal off cycle and higher power consumption. If cooling load is underestimated, the reliability and life time of the system will be shortened.

Aktacir et al. [81] studied the ambient variation impact to the selection of a constant air volume HVAC system for a high school block in Adana, Turkey. There were five data sets used in the study, in which the CURRENT represented the existing ambient design data [82] used for application in Turkey. The ASHRAE_MAX_04, ASHRAE_ MAX_1, ASHRAE_MAX_2 are the highest ambient data provided by ASHRAE [83]. Note that the ASHRAE_04, ASHRAE_1, ASHRAE_2, ASHRAE_EVAP_04, ASHRAE_EVAP_1, ASHRAE_EVAP_2

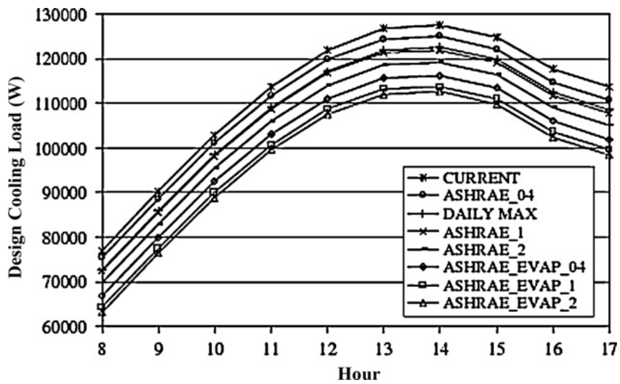

Fig. 15. Total design cooling load for all design data sets.

are the design conditions recommended by ASHRAE [65]. On the other hand, the DAILY MAX represented the highest ambient data daily of July 21st.

Fig. 15 shows the hourly cooling loads of the sample block based on a variety of ambient condition data sets. The existing design condition practiced by designers in Turkey indicates that the highest cooling load among all the conditions. Besides, an iterative approach-based computer program was written [84] to calculate the design capacities corresponding to different outdoor conditions. The result showed that the current design condition required the highest design capacity. Thus, the study implies that the existing ambient data practiced in Turkey for design are conservative and lead to over sizing and uneconomic. Besides, the cost analysis in the study suggests that the control system in the AC plant is critical, especially in energy saving aspect.

In Hungary, design of air conditioning systems is based on a determined modeling state, in which design parameters are generated from the weather database long time ago. However, climate change has resulted in an extreme summer and winter with a longer period. As a result, the current design practices in Hungary tend to underestimate the risk level during the summer and winter periods. Thus, a research was carried out [85] to develop a new risk-based modeling and revise the existing design values according to Hungary standard. In the research, a new weather database was initially generated through continuous measurements of climate data by a new measuring and data sampler system, i.e. TESTO 175-2 data logger, through samples taken every 5 min since 2003. The outdoor enthalpy was then calculated from the ambient data. Note that the medium surface temperature of the cooler and the temperature of the supply air were set to 13.5 °C and 21 °C, respectively. On the other hand, a mathematical model of the AC system was developed based on the probability theory, in which air condition values were categorized as continuous probability variable. Also, the distribution functions of the different outdoor climatic parameters were generated based on Gauss distribution. By utilizing theoretical and developed mathematical model as well as developed software, the cooling enthalpy can be determined for a measurement result in terms of distribution and density functions. Figs. 16 and 17 show the marked design enthalpy difference ($\Delta h = 12.5$ kJ/kg) on the x axis of the diagram and the point where the vertical line meets the function as indicated on the percentage axis. Thus, the value below the intersection line is at safe level. Conversely, the value above the point is considered at risk level. Note that the risk level during the most critical period (July to August) with respect to the cooling capacity from 2003 to 2005 is summarized in Table 2.

Some recent studies [87] claim that there is a very close relationship between the climatic elements, and any change in any of these elements, especially the solar radiation, affects the other elements as well. As a result, the combination of integrated

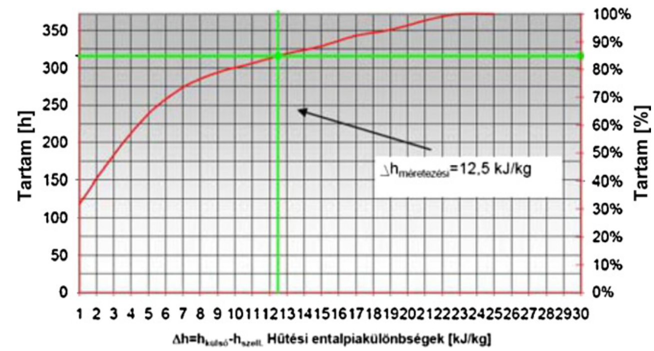

Fig. 16. Risk level at night half day July 2005, Budapest [86].

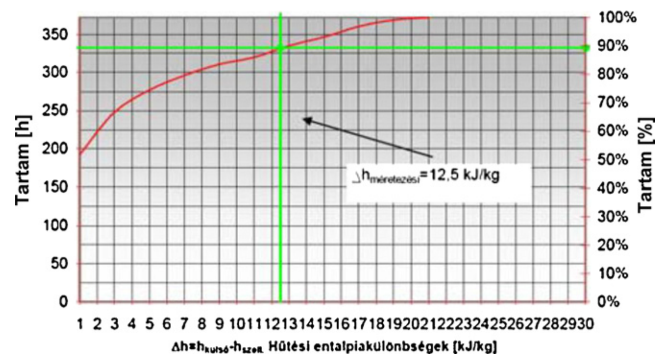

Fig. 17. Risk level at night half day August 2005, Budapest [86].

impacts on the weather element collection is needed to study the impact of weather on the overall energy performance [88,89]. Thus, Radhi [90] investigated the impact of the outdoor design condition on the accuracy of building energy analysis with respect to the climatic variability in Bahrain based on the complete climatic elements.

Two sets of measured data were collected initially based on the long term meteorological climatic elements provided by the Directorate of Meteorology of Bahrain. The solar data obtained from recent studies were then simulated in Bahrain [91,92]. Subsequently, two weather data files were generated using the MeteoNorm software [30], and then converted to binary files as the input to the building simulation software. This conversion was done in light of the design conditions of Bahrain indicated by ASHRAE [93]. In addition, two buildings subjected to an auditing and benchmarking process [94] were chosen, in which the first case building (Bldg-1) was a low rise office building oriented north to south and the second case building (Bldg-2) was a high rise commercial building constructed on a rectangular footing. Lastly, the Visual DOE program [95] was used to perform the building energy analysis and a comparison was conducted between results from the two sets of generated climate data with the actual consumption to check on

Table 2
The risk levels at half-day operation in July and August 2005, Budapest [87].

Half day operation (07:00 h–19:00 h) $t_{supply\ air} = 21\,°C$	
2003	
July	13.17%
August	22.58%
2004	
July	5.38%
August	1.88%
2005	
July	15.05%
August	0%

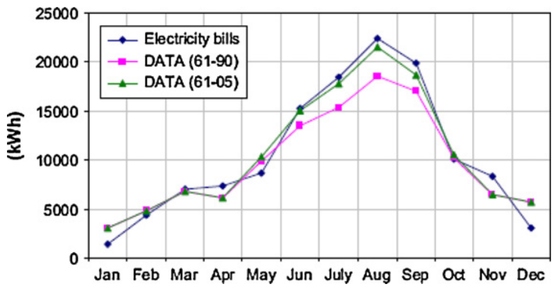

Fig. 18. Electricity consumption in Bldg-1.

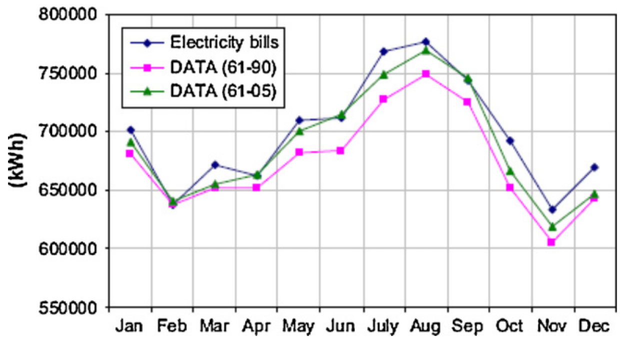

Fig. 19. Electricity consumption in Bldg-2.

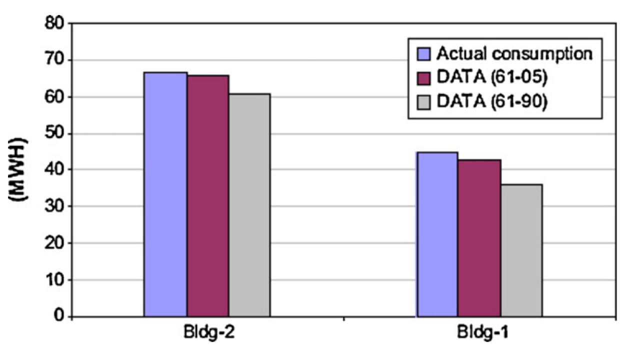

Fig. 20. Annual cooling load.

the reliability of the developed weather data files. The results are shown in Figs. 18–20.

The generated climate file is based on the past data (from 1961 to 1990) underestimating the electricity consumption by 14.5% and misrepresenting the cooling load by 5.9–8.9%. The weather file developed based on the recent data (from 1992 to 2005) underestimates the actual consumption by only 1.4%. The research concludes that the outdoor design condition must be updated from time to time and the latest weather data must be used in the thermal performance analysis in order to give a more accurate result.

5. Concluding summary

A comprehensive literature review has been conducted on the weather variation effects to the air conditioner performance as well as reliability. The review has shown that the climate change brings a significant effect on the building's cooling and heating load, the electricity consumption and the outdoor design conditions for the AC system globally. A numerous researches were carried out to study the impacts on the regional or global basis. However, most of the studies were based on the weather database long time back and only limited to the building energy analysis instead of the AC system itself. Therefore, substantial further investigations are certainly needed to examine on the climate varying effect to the AC system performance and reliability based on the latest and the predicted future climate data so that M&E engineers can take into the consideration of the possible climate change effects in the AC system design for the current and future uses.

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References

[1] Malaysia, General report of the Population and Housing Census, Department of Statistics Malaysia, 1970. Malaysia, General report of the Population and Housing Census, Department of Statistics Malaysia, 2000.
[2] Mahlia TMI, Masjuki HH, Choudhury IA. Potential electricity savings by implementing energy labels for room air conditioner in Malaysia. Energy Convers Manage 2002;43:2225–33.
[3] IEA. Oil crises and climate challenges: 30 years of energy use in IEA countries. Paris: International Energy Agency; 2004.
[4] Segal M, Shafer H, Mandel M, Alpert P, Balmor V. Climatic-related evaluations of the summer peak-hours' electrical load in Israel. J Appl Meteorol 1992;31:1492–8.
[5] Sailor DJ, Munoz JR. Sensitivity of electricity and natural gas consumption to climate in the USA-methodology and results for eight states. Energy 1997;22:987–98.
[6] Sailor DJ. Relating residential and commercial sector electricity loads to climate evaluating state level sensitivities and vulnerabilities. Energy 2001;26:645–57.
[7] IPCC. Climate change 2001: synthesis report, third assessment report. Cambridge: Intergovernmental Panel on Climate Change; 2002.
[8] Zimmerman KH. Heat pumps. Lewis Publishers; 1987.
[9] SIA standard 381/3: heating degree-days in Switzerland. Zurich, Switzerland: Swiss Association of Engineers and Architects; 1982 [in German].
[10] Christenson M, Manz H, Gyalistras D. Climate warming impact on degree-days and building energy demand in Switzerland. Energy Convers Manage 2006;47:671–86.
[11] Begert M, Seiz G, Schlegel T, Musa M, Baudraz G, Moesch M. Homogenization of measured time series of climatic parameters in Switzerland and computation of norm values 1961–1990 (in German). Final project report NORM90, MeteoSwiss, Zurich, Switzerland, 2003.
[12] Mearns LO, Hulme M, Carter TR, Leemans R, Lal M, Whetton P. Climate scenario development. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, et al., editors. Climate change 2001: the scientific basis. Cambridge, UK: Cambridge University Press, UK; 2001. p. 739–68.
[13] IPCC Data Distribution Centre: http://ipcc-ddc.cru.uea.ac.uk. Retrieved October 2004.
[14] Frank T. HELIOS-1 program manual. Dübendorf, Switzerland: Swiss Federal Laboratories for Materials Testing and Research (EMPA); 1982.
[15] LBL. DOE-2 Reference Manual Parts 1 and 2, Version 2.1A with 2.1B Supplements. Lawrence Berkeley Scientific Laboratories, Available from NTIS, National Technical Information Service, USA, 1980.
[16] BLAST (Building Loads Analysis and System Thermodynamics), 30 Mechanical Engineering Building, University of Illinois, 1266W. Green Street, Urbana, IL 61801, USA.
[17] Klein SA, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, et al. A Transient System Simulation Program. Madison, WI 53706 USA: Solar Energy Laboratory, University of Wisconsin-Madison; 2000.
[18] van Vuuren DP, van Ruijven B, Hoogwijk MM, Isaac M, de Vries HJM. TIMER 2: model description and application. In: Bouwman AF, Kram T, Klein Goldewijk K, editors. Integrated modelling of global environmental change. An overview of IMAGE 2.4. Bilthoven: Netherlands Environmental Assessment Agency (MNP); 2006, publication number 500110002/2006.
[19] Available from web site: http://www.eere.energy.gov/buildings/energyplus/.
[20] Cartalis C, Synodinou A, Proedrou M, Tsangrassoulis A, Santamouris M. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region. Energy Convers Manage 2001;42:1647–56.
[21] Mirasgedis S, Sarafidis Y, Georgopoulou E, Kotroni V, Lagouvardos K, Lalas DP. Modeling framework for estimating impacts of climate change on electricity demand at regional level: case of Greece. Energy Convers Manage 2007;48:1737–50.
[22] Frank T. Climate change impacts on building heating and cooling energy demand in Switzerland. Energy Buildings 2005;37:1175–85.
[23] Lam JC. Residential sector air conditioning loads and electricity use in Hong Kong. Energy Convers Manage 2000;41:1757–68.

[24] Lam JC, Tsang CL, Li DHW. Long term ambient temperature analysis and energy use implications in Hong Kong. Energy Convers Manage 2004;45:315–27.
[25] Li DHW, Wong SL, Lam JC. Climatic effects on cooling load determination in subtropical regions. Energy Convers Manage 2003;44:1831–43.
[26] Lam JC. Climatic influences on the energy performance of air-conditioned buildings. Energy Convers Manage 1999;40:39–49.
[27] Lin ZP, Deng SM. A study on the characteristics of nighttime bedroom cooling load in tropics and subtropics. J Build Environ 2004;39:1101–14.
[28] Adelard L, Boyer H, Garde F, Gatina JC. A detailed weather data generator for building simulations. Energy Buildings 2000;31:75–88.
[29] Petrakis M, Lykiudis S, Kassomenous P. A software tool for creation of a typical meteorological year. J Environ Softw 2000;4:221–7.
[30] Remund J, Lang R, Kunz S. MeteoNorm V.5.0 software and handbook on CDROM, vol. 14. Bern, Switzerland: Meteotest, Fabrikstrasse; 2003. p. 3012.
[31] Knight K, Klein S, Duffies JA. A methodology for the synthesis of hourly data. Sol Energy 1991;46:109–20.
[32] METEO—software tool for direct access to the ENAD-database. Dübendorf, Switzerland: Swiss Federal Laboratories for Materials Testing and Research (EMPA); 1988.
[33] Begert M, Seitz G, Schlegel T, Musa M, Baudraz G, Moesch M. Homogenization of measured time series of climatic parameters in Switzerland and computation of normalized values 1961–1990, Project Report NORM90, Federal Office of Meteorology and Climatology, Report No. 67, Zurich, 2003 [in German].
[34] METEONORM 3 solar engineering handbook version 3. Bern: Meteotest; 1995.
[35] Skartveit A, Lund H, Olseth JA. The design reference year. In: Recent advancements in solar radiation resource assessment, seminar. 1992.
[36] Skartveit A, Lund H, Olseth JA. The design reference year, DNMI Klima Report No. 11, Oslo, 1994.
[37] Lund H. The design reference year user manual, TU Denmark, Report No. 274, Lyngby, Denmark, 1995.40. K. Mathis, T.W. Püntener, DRY-Dataset for Switzerland, Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland, 1992.
[38] Lam JC, Chan ALS.Proc ANZAScA conf. Canberra. 1995.
[39] Goodsall CJ, Lam JC. A survey of building envelope designs for commercial buildings in Hong Kong. Build Res Inf 1994;22:79.
[40] Lam JC, Li DHW. Luminous efficacy of daylight under different sky conditions. Energy Convers Manage 1996;37:1703–11.
[43] Fagbenle RL. Generation of a test reference year for Ibadan, Nigeria. Energy Convers Manage 1995;36:61–3.
[44] ASHRAE handbook, fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2001.
[45] Al-Rabghi OM, Al-Beirutty MH, Fathalah KA. Estimation and measurement of electric energy consumption due to air conditioning cooling load. Energy Convers Manage 1999;40:1527–42.
[46] Tyler S. Household energy use and environment in Asian cities: an introduction. Energy 1994;19:503–8.
[47] Pongsapich A, Wongsekiarttirat W. Urban household energy consumption in Thailand. Energy 1994;19:509–16.
[48] Hills P. Household energy transition in Hong Kong. Energy 1994;19:517–28.
[49] Qiu D, Ma Y, Lu Y, Wang Q, Zhu Z. Household energy consumption in Beijing and Nanning, China. Energy 1994;19:529–38.
[50] Garcia RA, Manegdeg F, Raneses NO. Household energy consumption surveys in three Philippine cities. Energy 1994;19:539–48.
[51] Ang BW, Goh TN, Liu XQ. Residential electricity demand in Singapore. Energy 1992;17:37–46.
[52] SCECO. Technological conservation of electric energy consumption. In: A key lecture presented by the Ministry of Industry and Electricity to the 4th Saudi Engineering Conference. 1995 [in Arabic].
[53] IPCC. Climate change 2001. Impacts, adaptation and vulnerability. Geneva: Intergovernmental Panel of Climate Change; 2001.
[54] Intergovernmental Panel on Climate Change (IPCC) Working Group I. The physical basis of climate change; 2007, http://ipcc-wg1.ucar.edu/wg1/wg1-report.html/S.
[55] Munoz JR, Sailor DJ. A modeling methodology for assessing the impact of climate variability and climatic change on hydroelectric generation. Energy Convers Manage 1998;39:1459–69.
[56] Lehner B, Czisch G, Vassolo S. The impact of global change on the hydropower potential of Europe: a model based analysis. Energy Policy 2005;33:839–55.
[57] Breslow PB, Sailor DJ. Vulnerability of wind power resources to climate change in the continental United States. Renew Energy 2002;27:585–98.
[58] Pryor SC, Barthelmie RJ, Kjellstrom EP. Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model. Clim Dynam 2005;25:815–35.
[59] Lam CJ. Climatic and economic influences on residential electricity consumption. Energy Convers Manage 1998;39:623–9.
[60] Ranjan M, Jain VK. Modeling of electrical energy consumption in Delhi. Energy 1999;24:351–61.
[61] Moral-Carcedo J, Vicens-Otero J. Modeling the non-linear response of Spanish electricity demand to temperature variations. Energy Econ 2005;27:477–94.
[62] Robinson P. Modeling utility load and temperature relationships for use with long lead forecasts. J Appl Meteorol 1997;36:591–8.
[63] Pardo A, Meneu V, Valor E. Temperature and seasonality influences on Spanish electricity load. Energy Econ 2002;24:55–70.
[64] Mirasgedis S, Sarafidis Y, Georgopoulou E, Lalas DP, Moschovits M, Karagiannis F, et al. Models for mid-term electricity demand forecasting incorporating weather influences. Energy 2006;31:208–27.
[65] Scott MJ, Wrench LE, Hadley DL. Effects of climate change on commercial building energy demand. Energy Source 1994;16:17–32.
[66] Mayer LS, Benjamini Y. Modeling residential demand for natural gas as a function of the coldness of the month. Energy Buildings 1977;1:301–12.
[67] Le Comte DM, Warren HE. Modeling the impact of summer temperatures on national electricity consumption. J Appl Meteorol 1981;20:1415–9.
[68] Sailor DJ, Rosen JN, Munoz JR. Natural gas consumption and climate: a comprehensive set of predictive state-level models for the United States. Energy 1998;23:91–103.
[69] Kiattiporn W, Somchai M, Nipon K, Wattanapong R. The impacts of climatic and economic factors on residential electricity consumption of Bangkok Metropolis. Energy Buildings 2008;40:1419–25.
[70] Isaac M, Van Vuuren DP. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 2009;37:507–21.
[71] Schipper L, Meyers S. Energy efficiency and human activity. Cambridge, UK: Cambridge University Press; 1992.
[72] MNP. D-S.1 preliminary ADAM scenarios (deliverable for the ADAM project); 2007.
[73] Eley Associates Visual DOE-2.5 Developers, 142 Minna Street, San Francisco, CA 94105, USA, 1996.
[74] Al-Rabghi OM, Fathalah K, Al-Beirutty M. Final technical report on estimation and measurement of electric consumption due to air conditioning cooling load in building, King Abdulaziz University, Thermal Engineering Department, Funded Project No. 104/1417, 1998.
[75] Yan YY. Climate and residential electricity consumption in Hong Kong. Energy 1998;23:17–20.
[76] Parkpoom S, Harrison GP, Bialek JW. Climate change impacts on electricity demand. In: Proceedings of the 39th universities power engineering conference, vol. 2. 2004. p. 1342.
[77] Ruth M, Lin AC. Regional energy demand and adaptations to climate change: methodology and application to the state of Maryland, USA. Energy Policy 2006;34:2820–33.
[78] Amato A, Ruth M, Kirshen P, Horwitz J. Regional energy demand responses to climate change: methodology and application to the commonwealth of Massachusetts. Climatic Change 2005;71:175–201.
[79] Mansur E, Mendelsohn R, Morrison WA. Discrete–continuous choice model of climate change impacts on energy. Yale SOM working paper No. ES-43, 2005.
[80] ASHRAE handbook, fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 1993 [Chapter 24].
[81] Aktacir MA, Büyükalaca O, Bulut H, Yilmaz T. Influence of different outdoor design conditions on design cooling load and design capacities of air conditioning equipments. Energy Convers Manage 2008;49:1766–73.
[82] Önen E. Ventilation and air-conditioning. Technical publication no 9. Press of Prime Ministry, Turkish Ministry of Reconstruction and Settlement, Ankara, 1985.
[83] ASHRAE handbook, fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.; 2001.
[84] Aktacir MA. Influence of outdoor air conditions on operating capacity of air conditioning systems, PhD thesis, Çukurova University Institute of Natural and Applied Sciences, Adana, 2005.
[85] Vörös Sz KL. Influence of climate change on modelling of HVAC systems. In: Proceedings of the 2nd IASME/WSEAs international conference on Energy & Environment (EE'07). 2007.
[86] Gábor S. Klímatechnikai rendszerek kockázati elvű méretezése, BME Diplomaterv, Bp, 2003.
[87] Guan L, Yang J, Bell JM. Cross-correlation between weather data variables in Australia. J Build Environ 2007;42:1054–70.
[88] Clarke JA. Energy simulation in building design. 2nd ed. Oxford, Boston: Butterworth Heinemann; 2001.
[89] Straaten JF. Thermal performance of buildings. London, New York: Elsevier Publishing Company; 1967.
[90] Radhi H. A comparison of the accuracy of building energy analysis in Bahrain using data from different weather periods. Renew Energy 2009;34: 869–75.
[91] Al-Naser WE, Al-Attar R. Simple models for estimating the total, diffuse, direct and normal solar irradiation in Bahrain. Renew Energy 1999;18: 417–34.
[92] Muneer T, Alnaser WE, Fairooz F. The insulation on vertical surface having different direction in the Kingdom of Bahrain. Desalination 2007;209: 269–74.
[93] ASHRAE handbook, fundamental. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers; 2005.
[94] Radhi H, Sharples S. Benchmarking CO_2 emissions of office buildings in Bahrain. In: Proceedings of the 24th international conference on Passive and Low Energy Architecture (PLEA). 2007. p. 57–61.
[95] Architectural Energy Corporation. Visual DOE user manual. USA, 2004.

Further reading

[41] ASHRAE handbook, fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 1989.
[42] Hui SCM, Lam JC. Test reference year for comparative energy study. J Hong Kong Engineer 1992;20:13.